

## Impact of Recovery Characteristics on Switching Loss of SiC MOSFETs

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**Abstract.** The influence of the recovery characteristics on the switching behavior of SiC metal-oxide-semiconductor field-effect transistors (MOSFETs) with rated voltage and current of 1200 V and 50 A, respectively, at different switching speeds was investigated. A comparative analysis of the devices with different recovery characteristics revealed an increase in the turn-on loss ( $E_{on}$ ) owing to the higher output capacitance charge ( $Q_{oss}$ ) and reverse recovery charge ( $Q_{rr}$ ) in the recovery arm. On the other hand, a higher  $Q_{oss}$  in the recovery arm resulted in a lower turn-off loss ( $E_{off}$ ). In addition, an increase in  $Q_{oss}$  and  $Q_{rr}$  further influenced  $E_{on}$  and  $E_{off}$  at a higher switching speed. Furthermore, a higher  $Q_{rr}$  observed at a higher switching speed indicated a more significant impact of  $Q_{rr}$  on  $E_{on}$  at a high switching speed than that of  $Q_{oss}$ . The findings clarified in this study highlight the necessity of focusing the recovery characteristics to ensure a desirable switching loss of SiC MOSFETs.

### Introduction

Owing to their excellent material properties, SiC MOSFETs are regarded as promising candidates for future power electronics compared with commonly used Si insulated gate bipolar transistors (IGBTs). One of the main advantages of SiC MOSFETs over Si IGBTs is the significantly lower switching loss owing to the absence of the minority carrier storage. The resulting higher switching frequency operation of SiC MOSFETs in comparison with that of Si IGBTs enables the realization of a higher power density and lower energy consumption in the power electronics systems.

However, the switching loss of SiC MOSFETs could have a substantial impact on the total loss in high switching frequency operation [1–3]. Therefore, reducing the switching loss of SiC MOSFETs by increasing the switching speed for higher switching frequency operation is of significance.

Because of a higher  $Q_{oss}$  of SiC devices than that of Si devices, which is attributed to the two orders of magnitude higher doping concentrations of the drift layers, the displacement current of the free-wheeling diodes in the recovery arm during the switching process varies the drain current ( $I_d$ ) of the transistors in the switching arm, and thereby influences  $E_{on}$  and  $E_{off}$  [4]. Moreover, the influence of  $Q_{oss}$  on  $E_{on}$  is in a similar degree as that of  $Q_{rr}$ , which is derived from the parasitic body diodes of SiC MOSFETs in the recovery arm [4], although  $Q_{rr}$  dominates and  $Q_{oss}$  is negligible in Si devices [5].

In this study, the influence of  $Q_{oss}$  and  $Q_{rr}$  on the switching loss of SiC MOSFETs with different switching speeds was investigated in order to clarify the impact of the recovery characteristics under a higher switching speed.

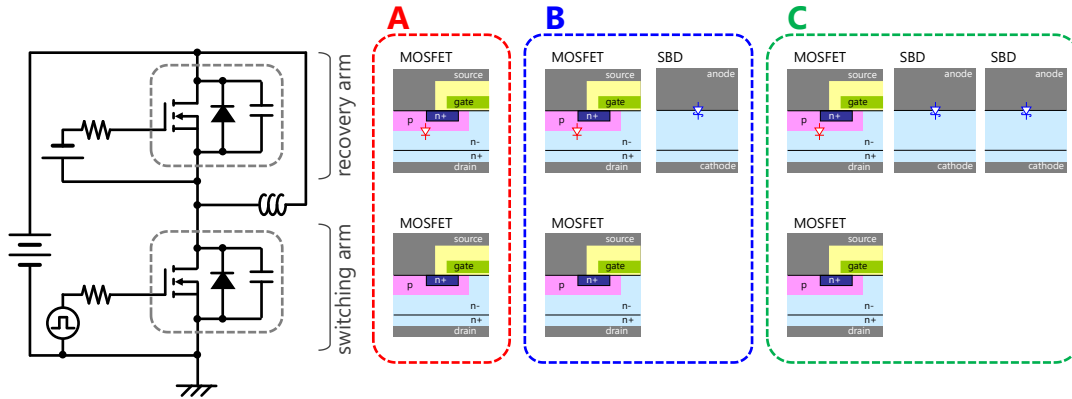


Fig. 1. Equivalent circuit for switching measurement, and three types of configurations investigated in this study.

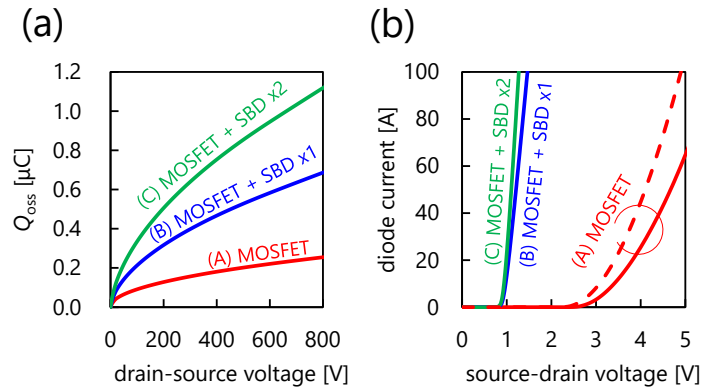


Fig. 2. (a) Simulated  $Q_{oss}$  and (b) measured diode characteristics of the recovery arm of each configuration at room temperature (solid lines) and 150 °C (a dashed line).

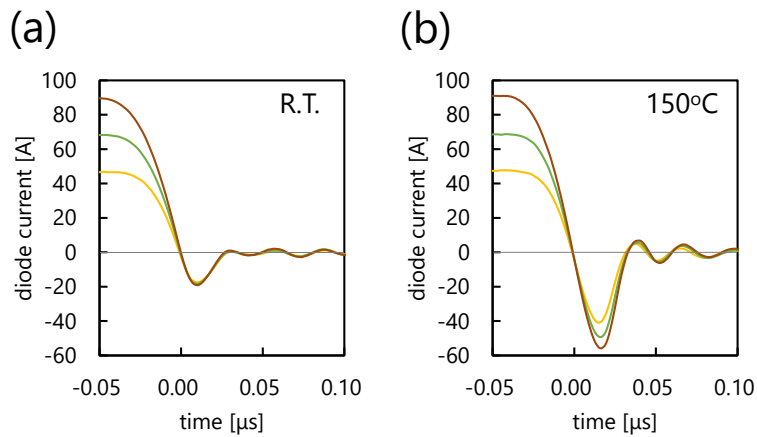


Fig. 3. Recovery waveforms of the configuration (A) at (a) room temperature and (b) 150 °C with several  $I_{sw}$  values.

## Experimental

Switching measurements were performed with a double pulse test using the equivalent circuit shown in Fig. 1. To clarify the influence of the recovery characteristics, three type of configurations, which are also depicted in Fig. 1, were investigated. The switching voltage was 600 V, which determines the  $Q_{oss}$  value in the switching measurements because it is derived from the charging or discharging current of the output capacitance in the recovery arm. The devices used in the recovery arm are (A) a MOSFET, (B) a MOSFET with an SBD, and (C) a MOSFET with two SBDs. The difference in  $Q_{oss}$  in the recovery arm of each configuration is displayed in Fig. 2(a), which is calculated using TCAD simulation. The higher  $Q_{oss}$  of (B) and (C) than that of (A) represents the

larger number of SBDs in the recovery arm. Fig. 2(b) shows the measured diode characteristics of the recovery arm for each configuration at room temperature (solid lines) and for the configuration (A) at 150 °C (a dashed line). The source-drain voltage of (B) and (C) is smaller than the built-in potential of the parasitic body diode of (A) up to the measured current range, indicating that the parasitic body diodes of (B) and (C) are not activated. The higher diode current of (A) at 150 °C than that at room temperature indicates the existence of minority carrier injection at a higher temperature. To clarify the difference in the minority carrier injection at different temperatures, the recovery waveforms of (A) at room temperature and 150 °C were evaluated by changing the switching current ( $I_{sw}$ ), as shown in Fig. 3. The reverse recovery current at room temperature shown in Fig. 3(a) is independent of  $I_{sw}$ , indicating a negligible influence of minority carrier storage. Therefore, the observed reverse recovery current is derived only from the displacement current due to  $Q_{oss}$ . On the other hand, as shown in Fig. 3(b), a higher  $I_{sw}$  results in a higher reverse recovery current at 150 °C, which indicates that the reverse recovery current consists of both  $Q_{oss}$  and  $Q_{rr}$ .

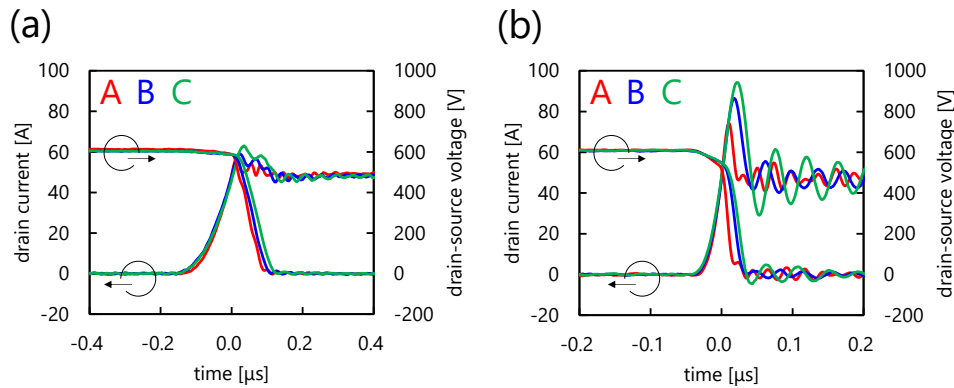


Fig. 4. Turn-on waveforms of each configuration at  $R_g$  of (a) 50  $\Omega$  and (b) 10  $\Omega$  at room temperature.

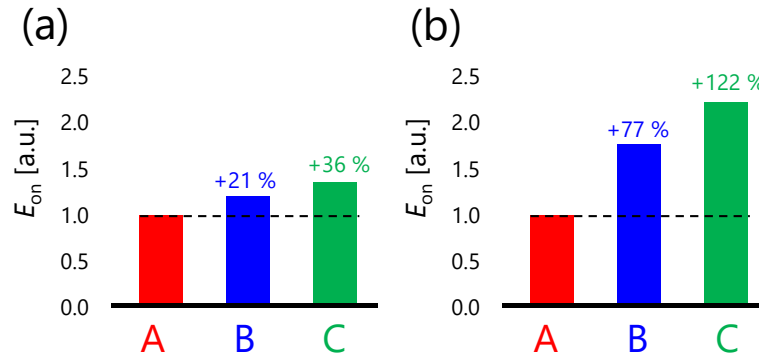


Fig. 5. Comparison of  $E_{on}$  for each configuration at  $R_g$  of (a) 50  $\Omega$  and (b) 10  $\Omega$  at room temperature.

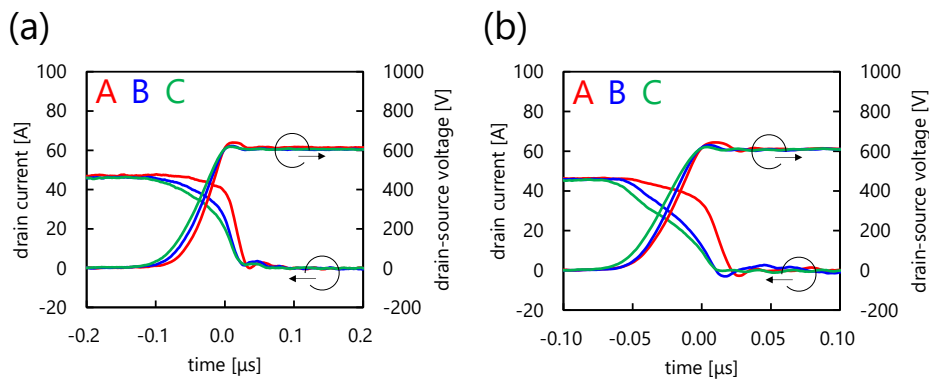


Fig. 6. Turn-off waveforms of each configuration at  $R_g$  of (a) 50  $\Omega$  and (b) 10  $\Omega$  at room temperature.

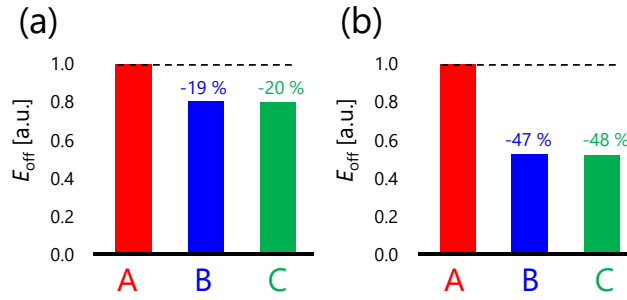


Fig. 7. Comparison of  $E_{off}$  for each configuration at  $R_g$  of (a)  $50 \Omega$  and (b)  $10 \Omega$  at room temperature.

## Results and Discussion

To clarify the influence of  $Q_{oss}$  in the recovery arm on the turn-on characteristics, Fig. 4 exhibits the turn-on waveforms of each configuration at  $R_g$  of (a)  $50 \Omega$  and (b)  $10 \Omega$  at room temperature. It should be noted that the  $Q_{rr}$  value in the configuration (A) is negligible at room temperature as discussed in Fig. 3. The  $I_d$  value during the variation in the drain-source voltage ( $V_{ds}$ ) is sum of the load current and charging current of the output capacitance in the recovery arm. Therefore, as shown in Fig. 4(a), a higher  $I_d$  peak of (B) and (C) than that of (A) is observed owing to the higher  $Q_{oss}$  of (B) and (C). The larger number of SBDs corresponds to the higher  $I_d$  peak of (C) than that of (B). Moreover, as shown in Fig. 4(b), the deviation in  $I_d$  peak between each configuration is higher at a higher switching speed, which can be derived from the faster charging time of the output capacitance in the recovery arm.

Fig. 5 shows the relative comparison of  $E_{on}$  of each configuration at  $R_g$  of (a)  $50 \Omega$  and (b)  $10 \Omega$  at room temperature. A higher  $Q_{oss}$  results in a higher  $E_{on}$ , and the influence of  $Q_{oss}$  is more emphasized for a lower  $R_g$  value. A larger impact of the difference in  $Q_{oss}$  between each configuration on  $E_{on}$  at a higher switching speed could correspond to the higher deviation in  $I_d$  peak, as shown in Fig. 4(b).

The turn-off waveforms of each configuration at  $R_g$  of (a)  $50 \Omega$  and (b)  $10 \Omega$  at room temperature are displayed in Fig. 6. As shown in Fig. 6(a), the lower  $I_d$  of (B) and (C) than that of (A) during the variation in  $V_{ds}$  is observed owing to the higher  $Q_{oss}$ , or higher discharging current of the output capacitance, of (B) and (C) in the recovery arm. In addition, the deviation in  $I_d$  between each configuration is higher at a higher switching speed, as shown in Fig. 6(b).

Fig. 7 shows the relative comparison of  $E_{off}$  of each configuration at  $R_g$  of (a)  $50 \Omega$  and (b)  $10 \Omega$  at room temperature. A higher  $Q_{oss}$  results in a lower  $E_{off}$ , and the influence of  $Q_{oss}$  is more emphasized for a lower  $R_g$  value due to the higher deviation in  $I_d$  (See Fig. 6(b)). However, unlike the case in the turn-on period, the  $E_{off}$  values of (B) and (C) are nearly equivalent despite the deviation in  $I_d$  derived from the difference in  $Q_{oss}$ . As can be seen in Figs. 6(a) and 6(b), the rate of change in  $V_{ds}$  ( $dV_{ds}/dt$ ) of each configuration also shows some deviation, and a higher  $Q_{oss}$  corresponds to a lower  $dV_{ds}/dt$ . A decrease in  $I_d$  could have an impact on reducing  $E_{off}$ , while a decrease in  $dV_{ds}/dt$  could result in a higher  $E_{off}$ . Therefore, the influence of the increased  $Q_{oss}$  on  $E_{off}$  is determined by the balance of the decreased  $I_d$  and  $dV_{ds}/dt$ .

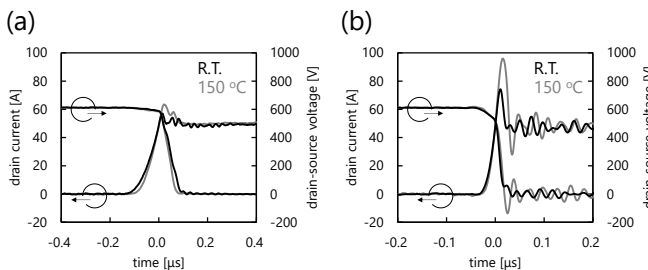


Fig. 8. Turn-on waveforms of the configuration (A) at  $R_g$  of (a)  $50 \Omega$  and (b)  $10 \Omega$  at room temperature (black lines) and  $150^\circ\text{C}$  (gray lines).

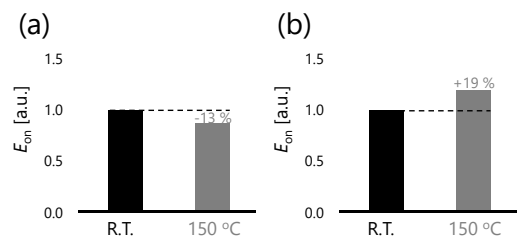


Fig. 9. Comparison of  $E_{on}$  for the configuration (A) at  $R_g$  of (a)  $50 \Omega$  and (b)  $10 \Omega$  at room temperature (black bars) and  $150^\circ\text{C}$  (gray bars).

In order to clarify the influence of  $Q_{tr}$  on  $E_{on}$ , the turn-on characteristics of the configuration (A) at room temperature and 150 °C were investigated. Fig. 8 shows the turn-on waveforms of (A) at each temperature at  $R_g$  of (a) 50  $\Omega$  and (b) 10  $\Omega$ . As shown in Fig. 8(a), a higher  $I_d$  peak at 150 °C than that at room temperature is observed. This phenomenon is owing to the higher  $Q_{tr}$  at 150 °C because  $Q_{tr}$  is negligible at room temperature, as discussed in Fig. 3, and  $Q_{oss}$  is independent of the measurement temperature. The deviation in  $I_d$  peak is higher in a higher switching speed, as shown in Fig. 8(b), which could be attributed to the faster reverse recovery time. Therefore, as shown in the comparative analysis of  $E_{on}$  at each temperature in Figs. 9(a) and 9(b), the  $E_{on}$  value at 150 °C is higher than that at room temperature at  $R_g$  of 10  $\Omega$ , while it is lower at  $R_g$  of 50  $\Omega$ .

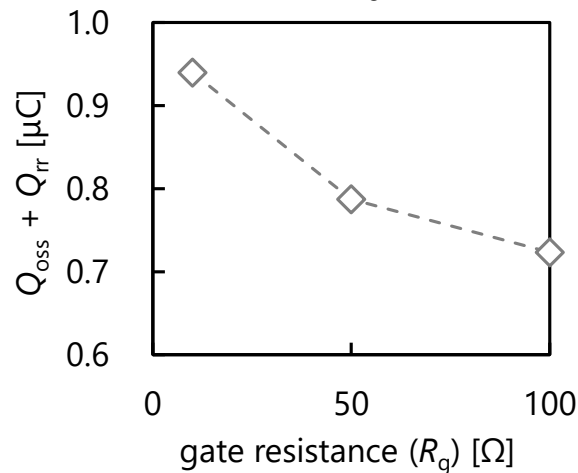


Fig. 10. Dependence of  $Q_{oss} + Q_{tr}$  on  $R_g$  for the configuration (A) at 150 °C.

Fig. 10 exhibits the total recovery charge ( $Q_{oss} + Q_{tr}$ ) as a function of  $R_g$  extracted from the measured waveforms at 150 °C. The total recovery charge at 150 °C is higher at a higher switching speed. Because  $Q_{oss}$  is independent of the switching speed, the observed dependence on  $R_g$  could be attributed to the variation in  $Q_{tr}$ . This result indicates a more significant impact of  $Q_{tr}$  on increasing  $E_{on}$  at a higher switching speed than that of  $Q_{oss}$ .

## Summary

In this study, we have experimentally revealed a larger impact of  $Q_{oss}$  and  $Q_{tr}$  on the switching loss of SiC MOSFETs at a higher switching speed. The results indicate the importance of paying attention to the recovery characteristics to ensure a desirable switching loss of SiC MOSFETs.

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